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CYLINDER-TEMPERATURE AND COOLING-AIR-PRESSURE INSTRUMENTATION FOR AIR-COOLED-ENGINE COOLING INVESTIGATIONS

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SUMMARY

A description of the types and the locations of pressure tubes and thermocouples satisfactorily used by NACA in multicylinder-engine cooling investigations is presented. The advantages and disadvantages of the various types of pressure tube and thermocouple are discussed with regard to reliability, durability, and ease of installation.

INTRODUCTION

Investigations of the cooling characteristics of air-cooled aircraft engines have utilized cooling-air-pressure and cylinder-temperature instrumentation that differs appreciably with respect to type, number, and location of pressure tubes and thermocouples. Some of the investigations have given misleading results because of inadequate or nonrepresentative pressure and temperature measurements. For example, large discrepancies were indicated between the cooling requirements of similar model engines as investigated in different installations. These discrepancies were greatly reduced, however, when proper choice of pressure tubes and thermocouples was made.

A description is given of the type, number, and location of pressure tubes and thermocouples satisfactorily used by the NACA in multicylinder-engine cooling research. The instrumentation given has been evolved from the results of numerous experimental investigations conducted during the period 1936-46 and is intended to give a representative and accurate measure of engine-cylinder temperatures and cooling-air pressures.

CYLINDER TEMPERATURES

Cylinder-Head Cooling Index

Because of its simplicity and convenience, a single spot temperature on the cylinder head is used to indicate the general cooling condition of the cylinder head. The maximum permissible value of this spot temperature (to give reliable engine operation) is determined by the engine manufacturer for each type and model engine from the results of a series of endurance tests conducted on the multicylinder engine. The types and the locations of thermocouples used for obtaining the cylinder-head cooling-index temperature are discussed in this section.

Rear-spark-plug-gasket thermocouple. - The usual practice in engine-cooling work has been to use the temperature of the rear-spark-plug gasket as the criterion of cooling. (See photograph of standard Army-Navy-Commerce (ANC) spark-plug-gasket thermocouple in fig. 1.) Although convenient for installation and maintenance, the use of the rear-spark-plug-gasket temperature as the engine-cooling criterion has been found to be unsatisfactory because the gasket thermocouple exhibits extreme temperature sensitiveness to local cooling-air conditions, tightness of spark plug, and other installation conditions, all of which vary appreciably among different installations, in particular, between the usual flight and test-stand investigations.

NACA rear-spark-plug-boss embedded thermocouple. - In order to reduce the errors resulting from the sensitivity of the gasket thermocouple to installation conditions, an alternative thermocouple embedded deep in the rear-spark-plug boss was developed at the NACA.

The location and installation details of the rear-spark-plug-boss embedded thermocouple are schematically shown in figure 2. The thermocouple is embedded at the bottom of a 0.107-inch-diameter hole drilled in the rear-spark-plug boss parallel to the axis of the spark-plug hole to a depth of 30 percent of the wall thickness at a distance 45/64 inch from the axis of the spark-plug hole, 45° down from the horizontal on the exhaust-port side of the boss. The iron-constantan thermocouple wires (28-gage glass-fiber insulated wires) are first soldered into a 0.107-inch-diameter soft brass pellet. This pellet is then inserted into and forced to the bottom of the thermocouple hole. A jig is used for quickly locating and drilling the thermocouple hole. As shown in the photograph of figure 3, the thermocouple wires are led to a clip screwed to a cylinder fin. Heavier wires are silver-soldered to the thermocouple wires at the clip.

The advantage of the boss-embedded thermocouple over the gasket thermocouple has been verified in experiments which show that the cooling of similar model engines in different installations is in closer agreement when the cooling is based on the boss-embedded-thermocouple reading than when based on the gasket-thermocouple reading. The boss-embedded thermocouple, however, lacks the ruggedness and durability required for service use and is therefore limited to use in engine-cooling investigations wherein the proper attention and care can be devoted to maintenance of the thermocouple.

Bayonet thermocouple. - The bayonet thermocouple, which is currently being used on some air-cooled engines in place of the rear-spark-plug-gasket thermocouple, is shown in detail in the photograph of figure 4. The thermocouple installation is as follows:

The ends of two insulated braided thermocouple wires are led through a stainless-steel protector tube and are embedded in a metal plug, which, in turn, is pressed into and soldered to the end of the protector tube. A spring around the tube is contained between a ridge located near the thermocouple end of the tube and a sliding clip located on the opposite end. As illustrated in figure 4, the thermocouple end of the protector tube is inserted in a hole in the cylinder-head wall. (For the engine cylinder shown in fig. 4, the hole is located just below the rear-spark-plug boss.) Attachment of the sliding clip to a mating clip screwed into the cylinder wall compresses the spring and presses the thermocouple end of the tube tightly against the end of the hole in the cylinder wall.

The bayonet thermocouple is of the contact type and is well adapted for ease of maintenance and handling in service. In order to check whether the bayonet thermocouple becomes inaccurate because of the change of contact conditions with operating time, such as may be caused by the presence of oil or dirt on the contact surface or by weakening of the bayonet spring and thus reduction of contact pressure, experiments were conducted on a double-row, radial, air-cooled engine equipped with bayonet thermocouples and instrumented, in addition, with boss-embedded thermocouples. Figure 5 presents the results of these experiments run over a period of 200 hours for a wide range of engine-operating and cooling-air conditions. These results show a consistent relation between the temperature indications of the bayonet and boss-embedded thermocouples for the entire period of operation. In view of its consistency of temperature indication, its ease of maintenance, and its ruggedness, the bayonet thermocouple is considered desirable for service use to provide an index of engine cooling. Care should be taken that the thermocouple hole and bayonet are clean before installation of the thermocouple.

Cylinder-Head Survey

Outside-wall-surface thermocouples. - In engine-cooling investigations, the cylinder-head cooling-index thermocouples are generally supplemented with additional thermocouples to survey the cylinder-head temperature distribution. Some of the locations on the cylinder head used for the temperature survey are indicated in the photograph of figure 6 and are outlined as follows:

(a) Front, rear, intake, and exhaust sides of head at level of top piston ring when piston is at top center, T1, T2, T3, and T4, respectively
(b) Side of exhaust chamber, T5
(c) Top of exhaust chamber, T6
(d) Above exhaust port, T7
(e) Above front spark plug, T8
(f) Center of crown (mid-dome), T9
(g) Above rear spark plug, T10
(h) Front of intake-valve-rocker housing, T11
(i) Top of intake chamber, T12
(j) Between rear spark plug and exhaust port, T13

The thermocouples (26-gage enamel-insulated iron and constantan wires) are peened into the cylinder wall between two adjacent fins. The following method of peening is illustrated in figure 7(a):

A 0.040-inch-diameter hole is drilled to a depth of 1/32 inch into the cylinder wall at the required location between two adjacent cylinder fins. The thermocouple junction is placed in the hole and the metal around the hole is peened with the aid of a peening tool to grip the thermocouple tightly in place. Sleeving is slipped over each thermocouple wire for additional protection; the two covered wires are then supported near the tip of a fin.

Special thermocouples. - Deep-embedded thermocouples are used for measuring the temperature of such cylinder-head internal regions as the exhaust-valve guide and seat.

The method of embedding a thermocouple deeply in the cylinder wall is illustrated in figure 7(b) for an exhaust-valve guide. A 1/16-inch-diameter hole is first drilled into the cylinder-wall to within 1/32 inch of the required thermocouple position. A 0.040-inch-diameter hole is then drilled at the bottom of this first hole to a depth of 1/32 inch. The thermocouple junction is peened into the small hole. A hollow peening tool (shown in fig. 7(b)) is used in order to clear the thermocouple wires. For protection, a two-hole Alundum tube is slipped over the thermocouple wires to the bottom of the large hole; the large hole is then filled with high-temperature-resistant plastic cement.

Special techniques have been developed by the NACA for measuring the temperatures of the piston and the exhaust valve in single-cylinder tests. These techniques are described in detail in references 1 and 2.

Cylinder-Barrel Cooling Index

Barrel-flange thermocouples. - A thermocouple embedded in the barrel flange at the rear of the cylinder is commonly used to indicate the cooling condition of the cylinder barrel. A photograph of the standard ANC flange thermocouple is presented in figure 8. The thermocouple installation consists of two 14-gage heavily insulated wires (iron and constantan); one end of each wire is bared and then pressed into and sweated to a 1/8-inch-diameter, 1/4-inch-length copper sleeve. The sleeves are peened into two holes drilled in the cylinder flange.

The former practice at the NACA was to substitute a thermocouple spot-welded to the flange for the flange-embedded thermocouple. In recent multicylinder-engine investigations at the NACA, however, cylinder failures that have occurred at the flange have been attributed to the thermal stresses produced in spot-welding, and the use of a spot-welded flange thermocouple has been discontinued.

The foregoing thermocouple installations are sufficiently rugged for service use; however, the flange location is not considered the most suitable location for obtaining temperature measurements indicative of the over-all cooling conditions of the barrel.

Barrel-finning thermocouples. - The locations generally used instead of the flange are at the rear of the cylinder about one-half and about two-thirds of the barrel finning up from the bottom barrel fin (T15 and T19, respectively, fig. 6(b)). For these locations, the thermocouple is closer to the top-piston-ring zone of action than for the flange location; for current engines, the two-thirds position corresponds roughly to the level of the top piston ring at piston midstroke.

At the NACA, the thermocouples (26-gage iron and constantan wires) in the barrel finning are merely peened into the barrel wall (or the muff) in the manner previously described for the cylinder-head-survey thermocouples. Such a thermocouple installation is satisfactory for engine-cooling investigations but lacks the ruggedness required for service.

Cylinder-Barrel Survey

Some of the locations on the cylinder barrel used for obtaining the barrel temperature distribution are also indicated in the photographs of figure 6 and are:

(a) Rear of barrel, one-third of barrel finning up from bottom fin, T14

(b) Front, intake, and exhaust sides of barrel, half-way up barrel finning, T16, T17, and T18, respectively.

The thermocouples are peened into the barrel wall (or the muff).

COOLING-AIR PRESSURES

Engine cooling-air pressure surveys conducted at the NACA on numerous test-stand and flight installations show that the total and static pressures ahead of and behind the engine vary appreciably with location. The surveys also show that the pressure distributions are greatly influenced by the cowl design, by the cowl attitude with respect to the incoming air, and by the location and the deflection of the cowl flaps. In installations in which the propeller sets up considerable swirl in the cooling air, appreciable difference exists between the total pressures at the fin-passage entrances of the two sides of a cylinder. Obstructions to the air flow, such as distributors, magnetos, manifolds, and valve push-rod guides, also affect the pressure distributions. Because of the sensitivity of the cooling-air pressures to location, to design of installation, and to operating conditions, the current practice in engine-cooling investigations is to employ a large number of total- and static-pressure tubes in the measurement of the average cooling-air pressure drop across the engine. The cooling-air pressure drop, which includes a complete loss in velocity head at the rear of the engine, is the difference between the average total pressure ahead of the engine and the average static pressure behind the engine.

Types of pressure tube. - The total pressure ahead of a cylinder is measured with either a shrouded total-head tube installed directly in front of the cylinder or with an open-end tube installed between the fin tips and the cylinder baffle slightly behind the baffle entrance. (See fig. 9.)

The shrouded total-head tube is insensitive to angle of flow up to 60°. Some of the shroud designs used are shown in figure 10; inasmuch as the accuracy of the pressure indications is substantially unaffected by the design of the shroud-venturi inner wall, design 3 (fig. 10(c)) is preferable because of simplicity of construction. The tube is somewhat difficult to use because of the support and bracketing problems.

The total-pressure indications of the open-end tube are normally quite sensitive to angle of flow; however, when located as shown in figure 9, the open-end tube is so effectively shielded by the baffle and the cylinder as to be substantially unaffected by the direction of approach of the air to the cylinder. The details of installation of an open-end tube (3/16- to 1/4-in. stainless-steel or copper tubing) on a cylinder baffle are shown in figure 11. The open end of the tube is located about 1/8 inch behind the baffle entrance; slight deviations from this position have no effect on the accuracy of the pressure indications.

For the measurement of the rear static pressures, both closed-end static-pressure tubes supported in the air stream directly behind the cylinder and open-end tubes so located on the baffle rear as to receive no velocity pressure have been successfully used. Both types of tube are shown in figure 12 at the various locations that have given reliable results. Details of the closed-end static tube are given in the sketch of figure 13. The installation of the open-end tubes (3/16- to 1/4-in. stainless-steel or copper tubing) at the shielded locations on the side baffles is shown in figure 14. The open-end static tube in the shielded locations is usually preferred to the closed-end static tube because of convenience of installation and also because of the sensitivity of the closed-end static tube to direction of air flow.

Basic pressure-tube installation on radial single-row engines. - The cooling-air total pressure ahead of the engine is measured with open-end tubes H1, H2, H3, H4, and H5 located on each cylinder at the positions indicated in figure 15. Tube H1 is located at the top of the head in line with the front and rear spark plugs; tubes H2 and H3 are located at the level of the middle circumferential head fin; and tubes H4 and H5 are located two-thirds of the way up the barrel finning. The cooling-air static pressure behind the engine is measured at the rear of each cylinder with open-end tubes placed in shielded positions, as indicated in figure 16. Tube P1 is installed in the stagnation region behind the cylinder top baffle and tubes P3 and P5 are installed in the rear curl of the intake-side baffle at right angles to the general direction of the air flow. Tubes P3 and P5 are at the same level as tubes H3 and H5, respectively.

Any tubes that lie in the wake of an obstruction are moved out of the wake as close to the originally intended location as possible.

Basic pressure-tube installation on radial multirow engines. - The basic pressure-tube installation for the multirow engine is the same as that described for the single-row engine with the following exceptions:

(a) Only the front of the front-row cylinders of the multirow engine is instrumented with total-head tubes for measuring the total pressure ahead of the engine.

(b) Only the rear of the rear-row cylinders of the multirow engine is instrumented with static-pressure tubes for measuring the static pressure behind the engine. The front total-pressure-tube installation for the front-row cylinders and the rear static-pressure-tube installation for the rear-row cylinders are thus the same as those described for the front and rear of the cylinders of the single-row engine, respectively, (figs. 15 and 16).

Additions to tubes of basic installation. - Although the basic pressure tubes are satisfactory for instrumentation of most engine installations, additions to the basic pressure tubes may be required for some engine installations. Some of the pressure tubes used to supplement the basic installation are outlined as follows:

(a) Open-end total-head tubes at baffle entrance on exhaust side of cylinder at level of exhaust-port axis and at level of bottom barrel fin (designated H6 and H7 in fig. 9)

(b) Shielded total-head tubes supported directly in front of
828 cylinder head and barrel (H8 and H9 in fig. 9)

(c) Closed-end static tubes supported in air stream parallel to the general direction of flow directly behind cylinder head and barrel (P8 and P9 in fig. 12)

(d) Open-end static tube located just above cylinder flange in shielded position at rear of cylinder (P7 in fig. 12)

The choice of these tubes for each engine installation should be based on consideration of the probable effects of the flow paths to and from the engine on the flow conditions at the front and rear faces of the engine. These additional tubes may be especially required in engine installations wherein the pressure gradients ahead of and behind the engine are steep and erratic, such as would be caused by a high-velocity blast of air directed at a portion of the cylinders (found to occur in cowls with high-velocity inlets and short high-angle diffusers) or by extensive blockage in the flow paths to and from the engine. In general, such flow conditions are to be avoided because of the large pressure losses ahead of and behind the engine and because of the highly nonuniform cooling involved, which results in radical departure of the cylinder-temperature distribution from that obtained in the usual engine-development and endurance tests.

In addition to the use of more tubes in the pressure measurements, the basic installation may be expanded to instrumentation of the cylinders in other rows of the multirow engine; that is, the front of the cylinders in the intermediate and rear rows may also be instrumented with total-head tubes and the rear of the cylinders in the intermediate and front rows may also be instrumented with static tubes.

The expanded pressure-tube installation permits closer study of the details of the air flow. From this study the tubes that should be added to the basic installation, if any, to give the best measure of average pressure drop can be determined.

<u>Pressure-tube installation used on in-line air-cooled engine.</u> - Inasmuch as most medium- and high-power air-cooled engines are of the radial type, little cooling work has been done on the in-line air-cooled engine. The pressure-tube installation satisfactorily used in one unpublished cooling project at the NACA on an in-line air-cooled engine is presented in figure 17, which shows the configuration of the engine cylinders and the types and locations of pressure tubes installed on each cylinder.

CORRELATION OF ENGINE-COOLING DATA

A method was developed in reference 3 for conveniently relating the average temperature of an air-cooled engine to the cooling-air and engine operating conditions. This method greatly reduces the amount of investigation required to establish the cooling characteristics of an engine and greatly simplifies the correlation of the experimental data. The detailed application of the correlation method is illustrated in reference 4.

In engine-cooling correlation work, the cooling-air pressure drops across the engine heads and across the barrels are determined separately: The cooling-index temperature for the engine heads is correlated with the pressure drop across the heads and the cooling-index temperature for the engine barrels is correlated with the barrel pressure drop. The head cooling-index temperature is taken as the average for all the engine cylinders of the temperature indications of the cylinder-head cooling-index thermocouples; the barrel cooling-index temperature is taken as the average for all the engine cylinders of the barrel cooling-index thermocouples. For the basic pressure-tube installation, the average of the readings of tubes H1, H2, and H3 for all the engine cylinders (fig. 15) is taken as the average pressure in front of the engine heads; the average of the readings of tubes H4 and H5 is taken as the average pressure in front of the engine barrels. The average of the readings of tubes P1 and P3 (fig. 12) is taken as the average pressure behind the engine heads; the average of the readings of tubes P5 is taken as the average pressure behind the engine barrels.

Accurate measurement of the engine operating conditions (in particular, of charge-air and fuel flows) as well as of the cooling-air conditions is required for proper establishment of the engine cooling characteristics. Typical experimental methods in flight and on a test stand are described in references 5 and 6.

Flight Propulsion Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, September 9, 1947.

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2. Sanders, J. C., Wilsted, H. D., and Mulcahy, B. A.: Operating Temperatures of a Sodium-Cooled Exhaust-Valve as Measured by a Thermocouple. NACA Rep. No. 754, 1943.

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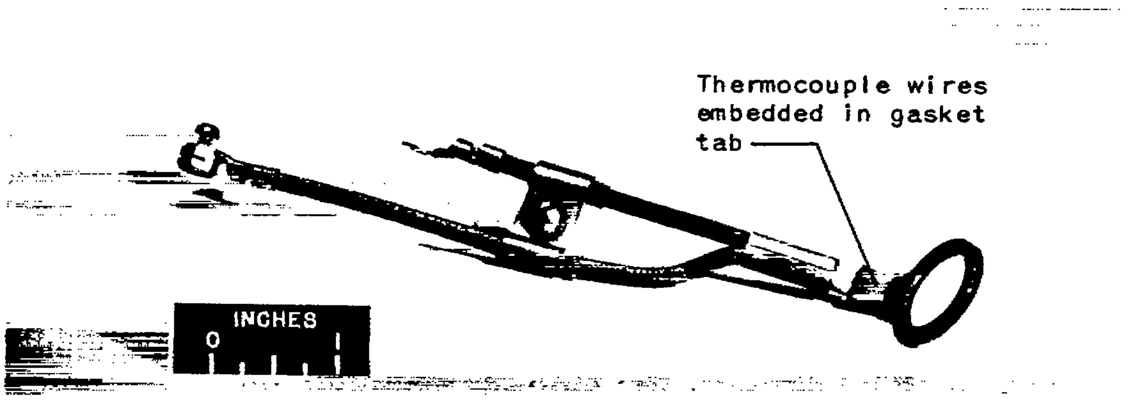
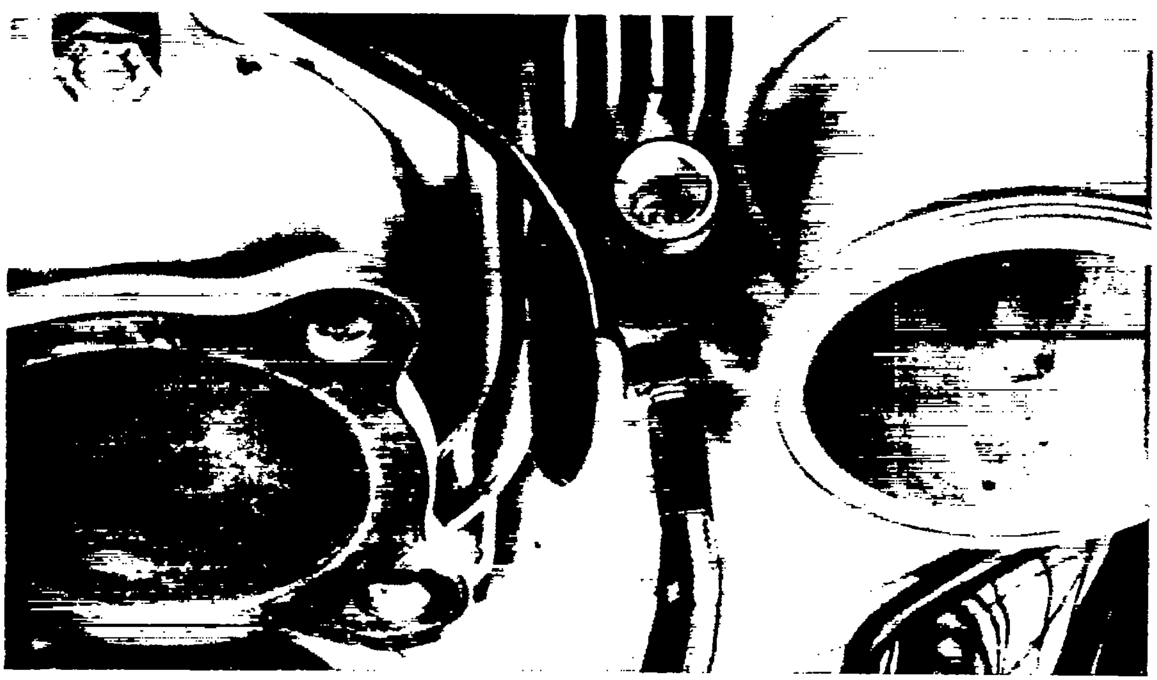
4. Pinkel, Benjamin, and Rubert, Kennedy F.: Correlation of Wright Aeronautical Corporation Cooling Data on the R-3350-14 Intermediate Engine and Comparison with Data from the Langley 16-Foot High-Speed Tunnel. NACA ACR No. E5A18, 1945.

5. Manganiello, Eugene J., Valerino, Michael F., and Bell, E. Barton: High-Altitude Flight Cooling Investigation of a Radial Air-Cooled Engine. NACA TN No. 1089, 1946.

6. Valerino, Michael F., Kaufman, Samuel J., and Hughes, Richard F.: Effect of Exhaust Pressure on the Cooling Characteristics of an Air-Cooled Engine. NACA TN No. 1221, 1947.



(a) Thermocouple details.



(b) Thermocouple installation.

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Figure 1. - Standard Army-Navy-Commerce spark-plug-gasket thermocouple.

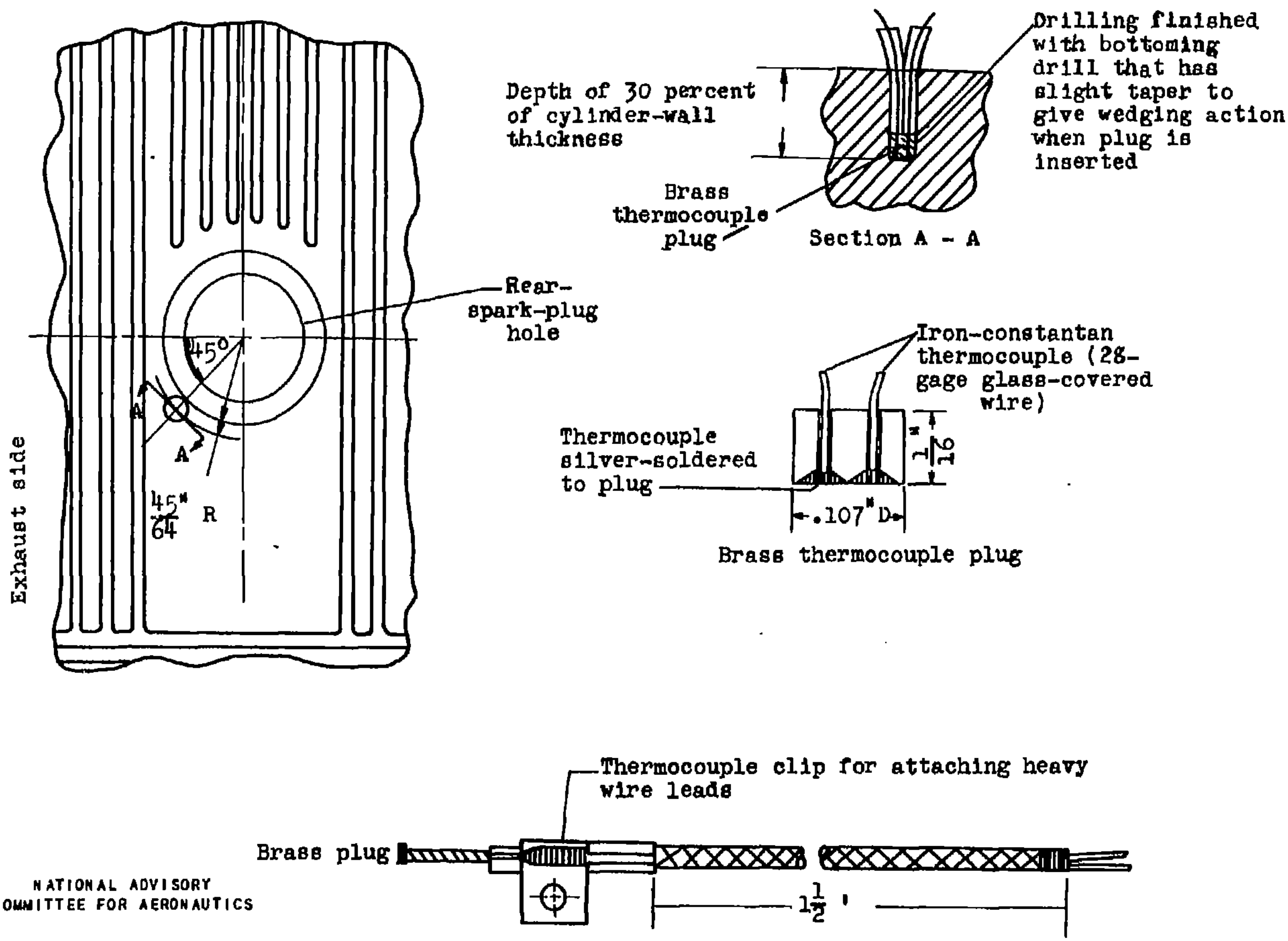

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Figure 2. - NACA rear-spark-plug-boss embedded thermocouple.

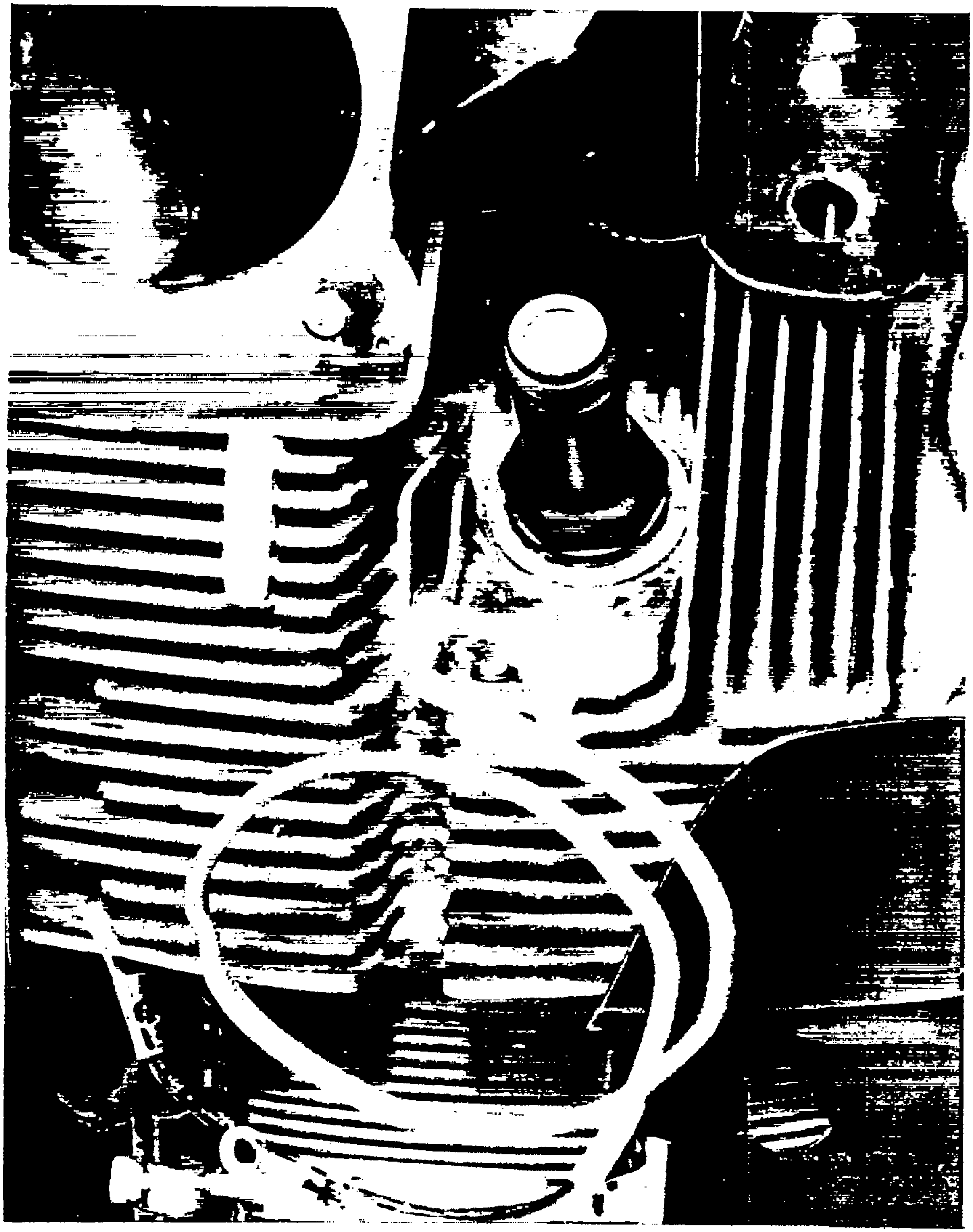

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Figure 3. - Installation of NACA rear-spark-plug-boss embedded thermocouple.

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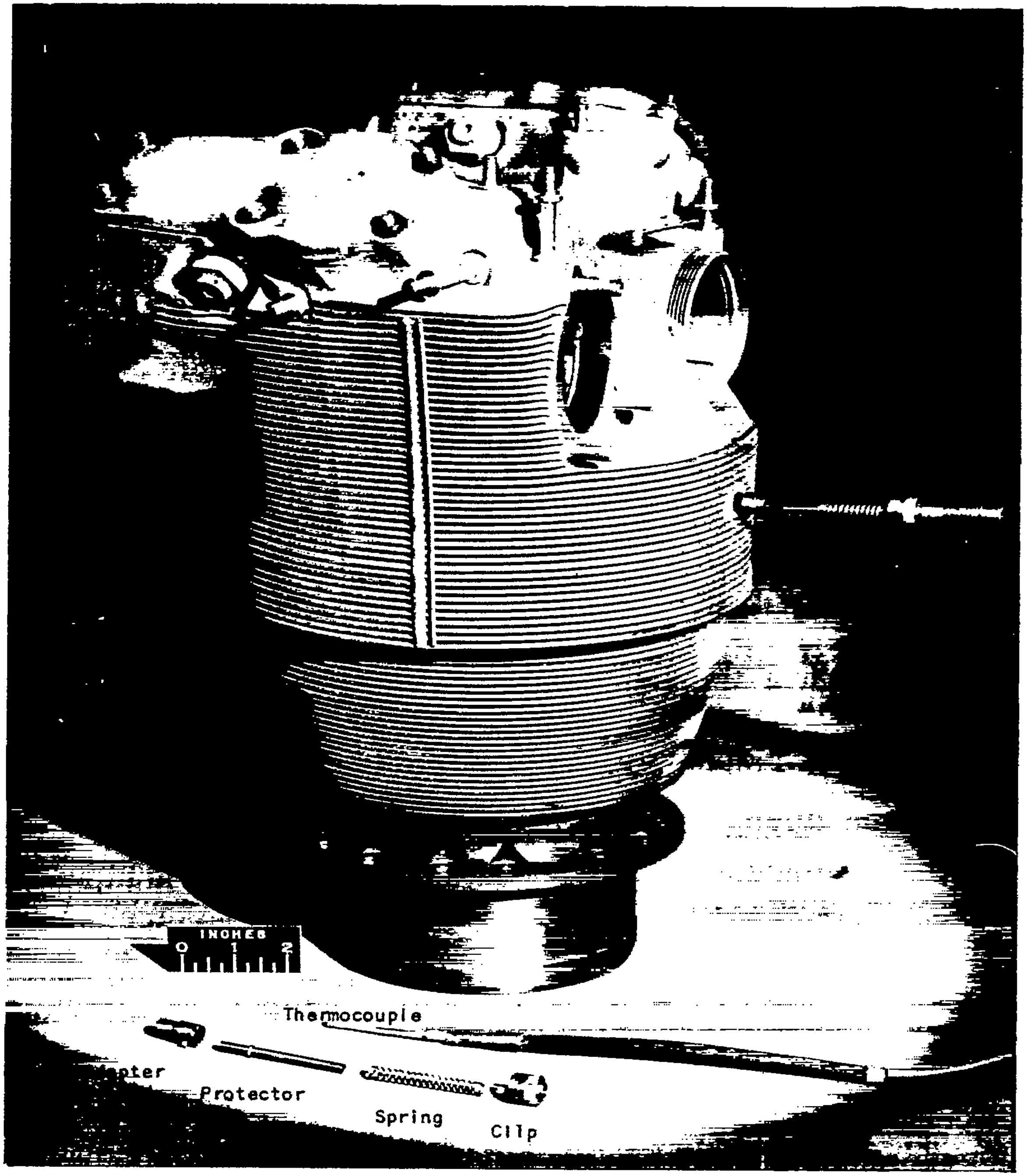

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Figure 4. - Installation of bayonet thermocouple.

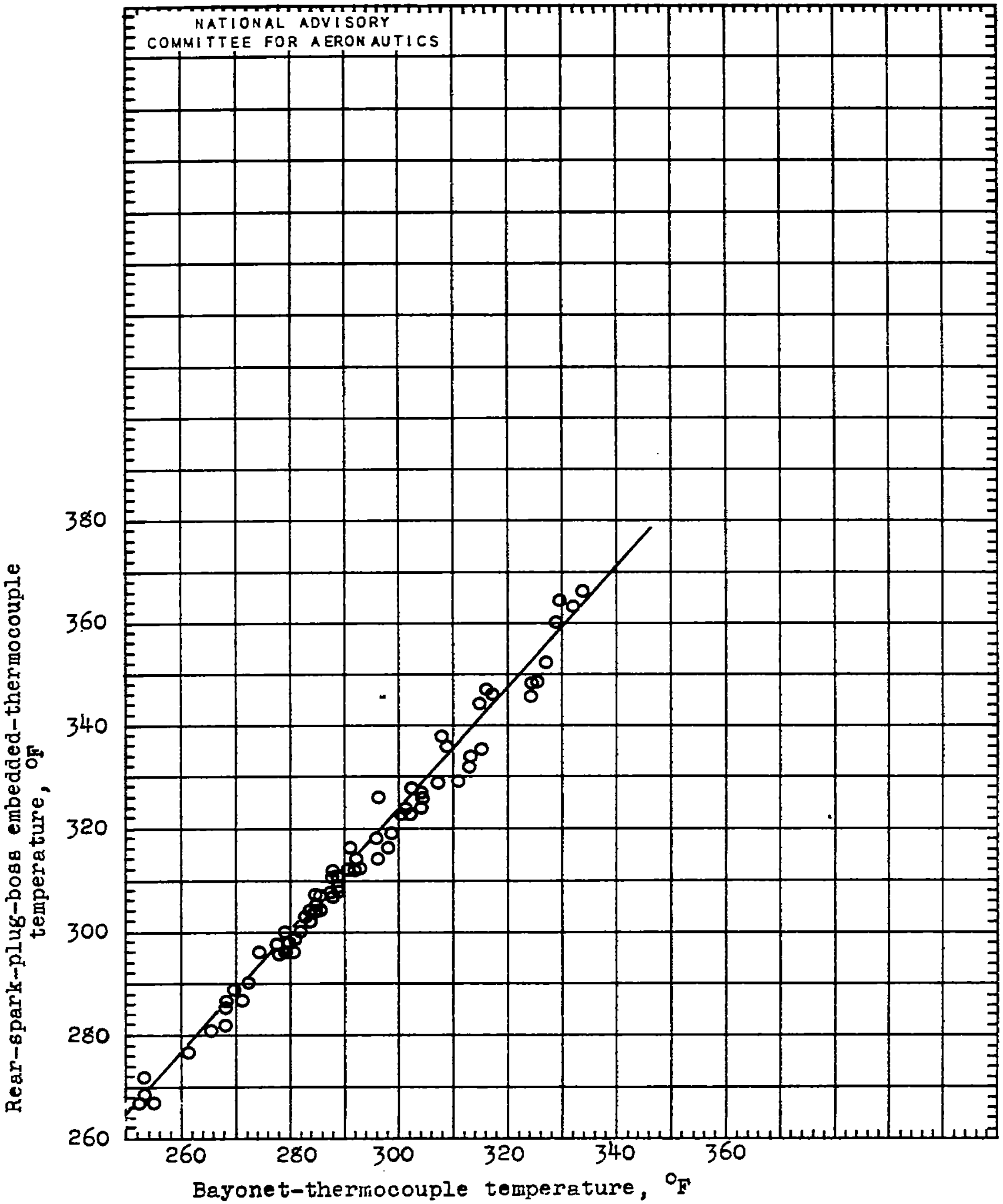

Figure 5. - Comparison of temperature indications of rear-spark-plug-boss embedded and bayonet thermocouples. Total running time, 200 hours.

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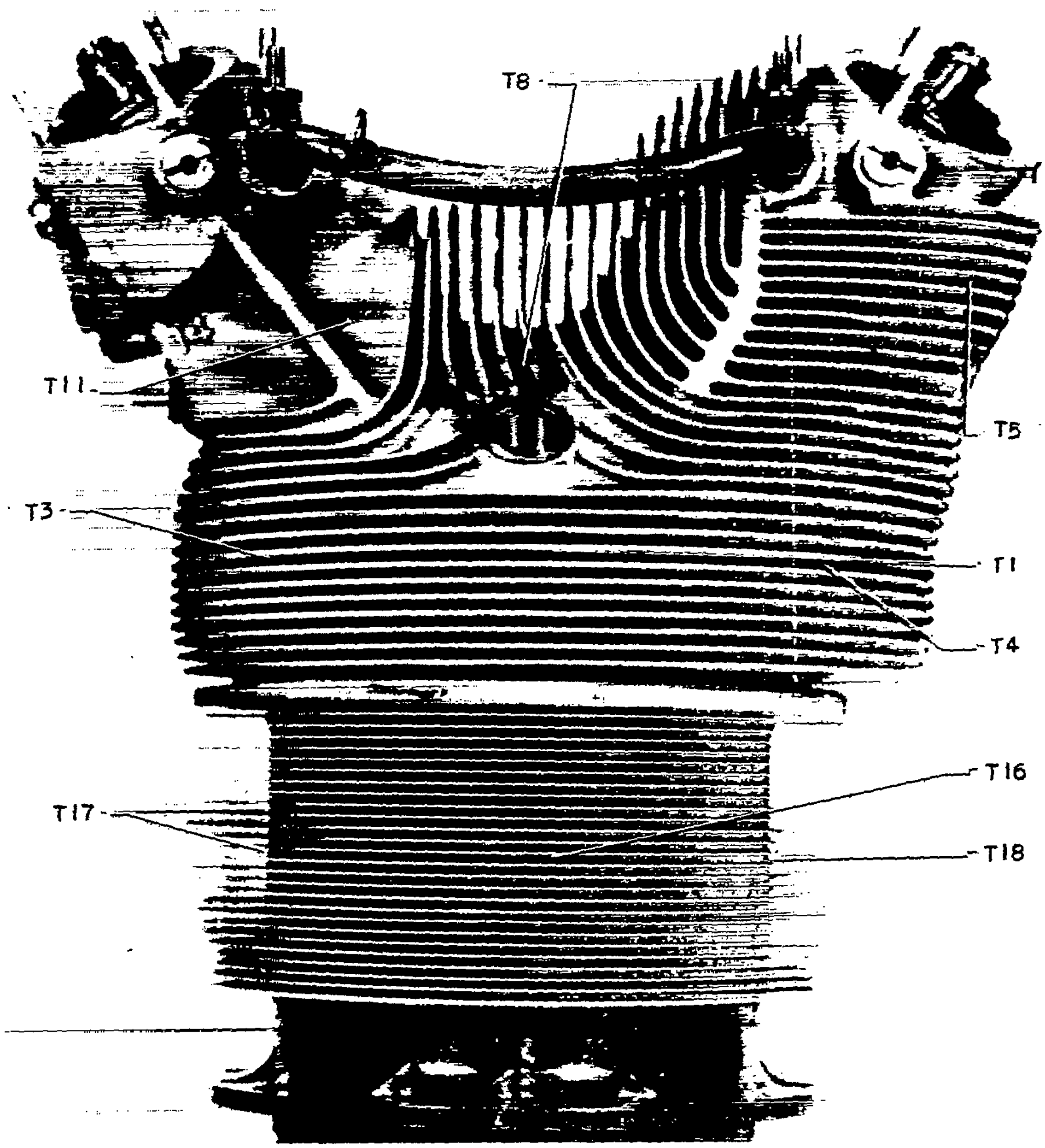

(a) Front view.

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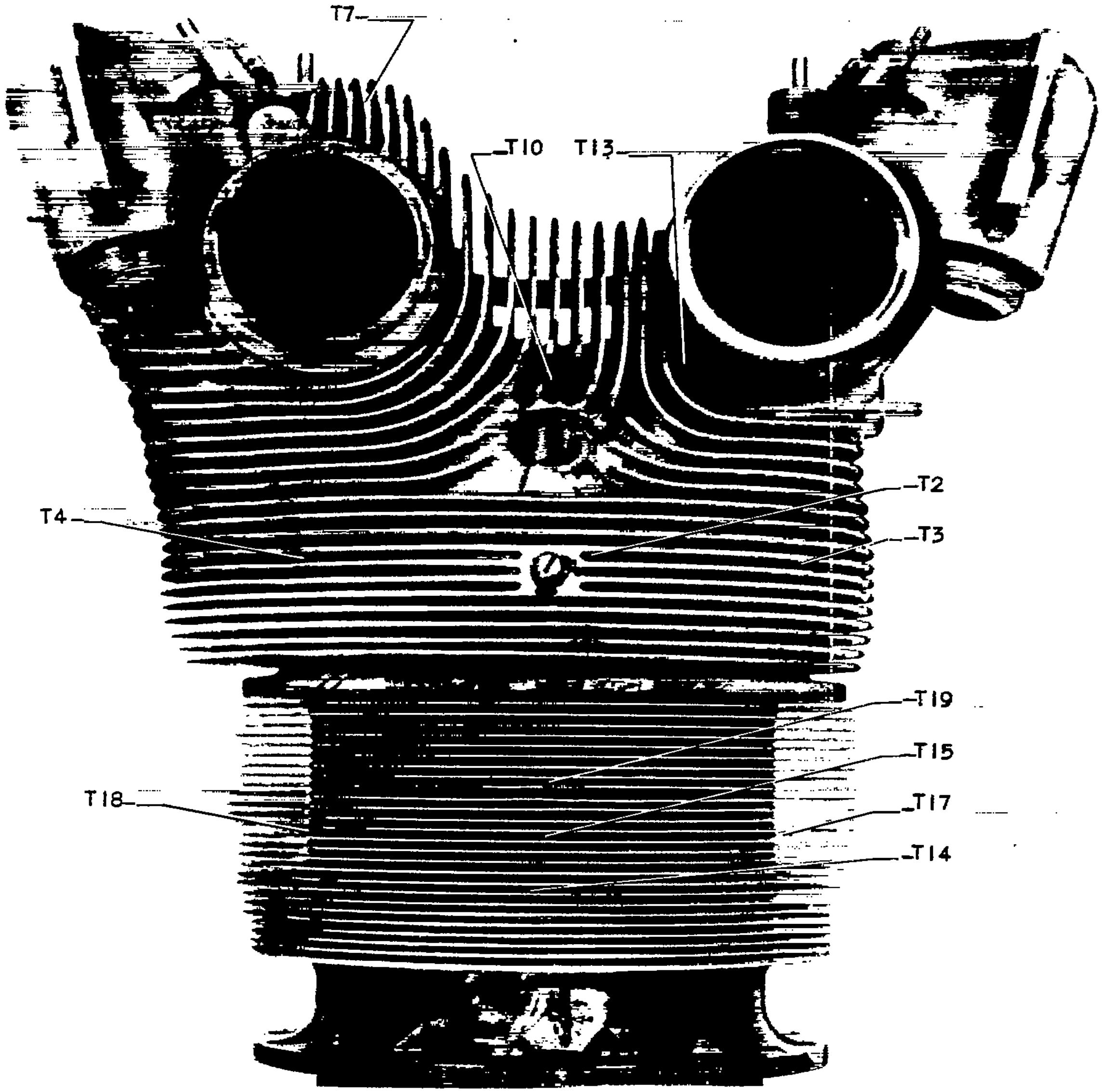
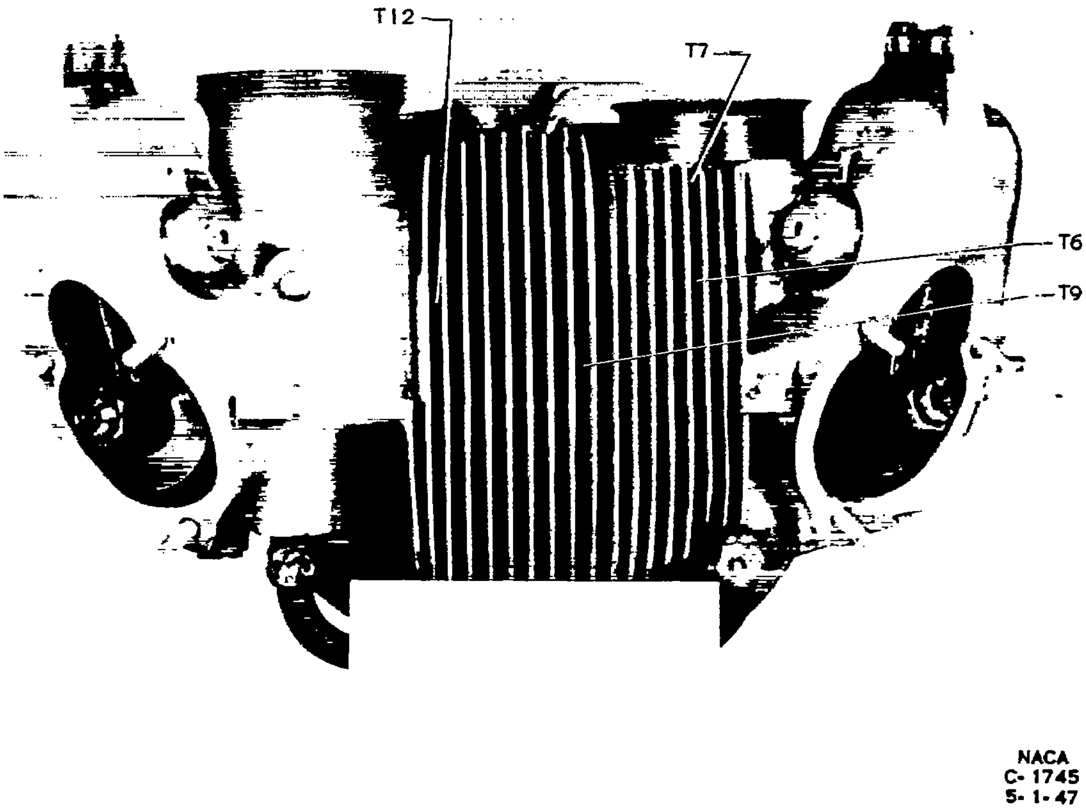
Figure 6. - Locations of thermocouples on cylinder.



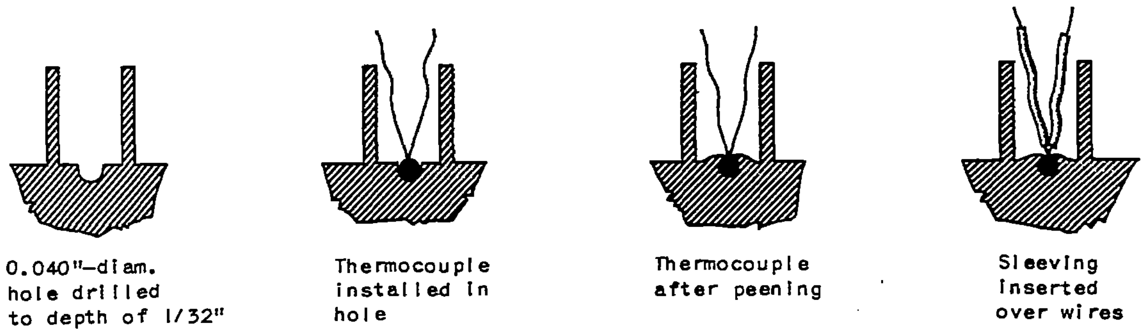
(b) Rear view.

Figure 6. - Continued. Locations of thermocouples on cylinder.

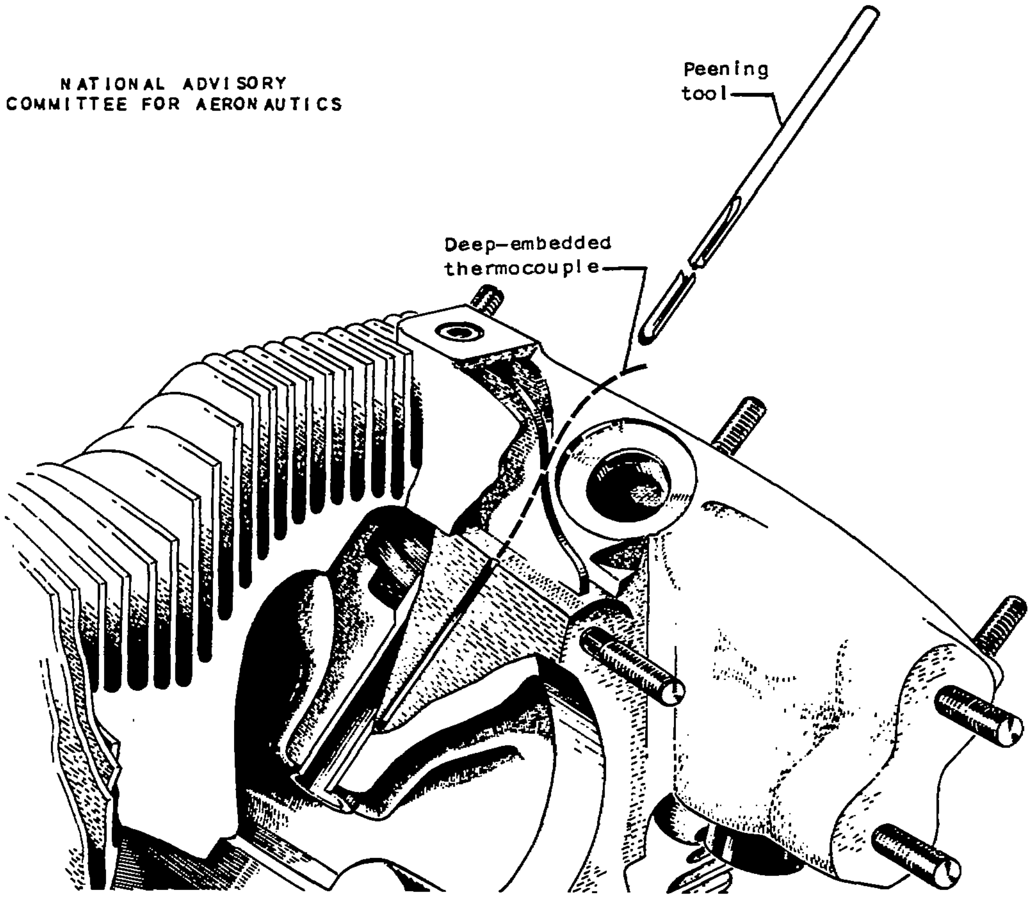


(c) Top view.

Figure 6. – Concluded. Locations of thermocouples on cylinder.



(a) Shallow-embedded thermocouple.



(b) Deep-embedded thermocouple.

Figure 7. - Schematic diagram illustrating method of peening thermocouple into cylinder wall.

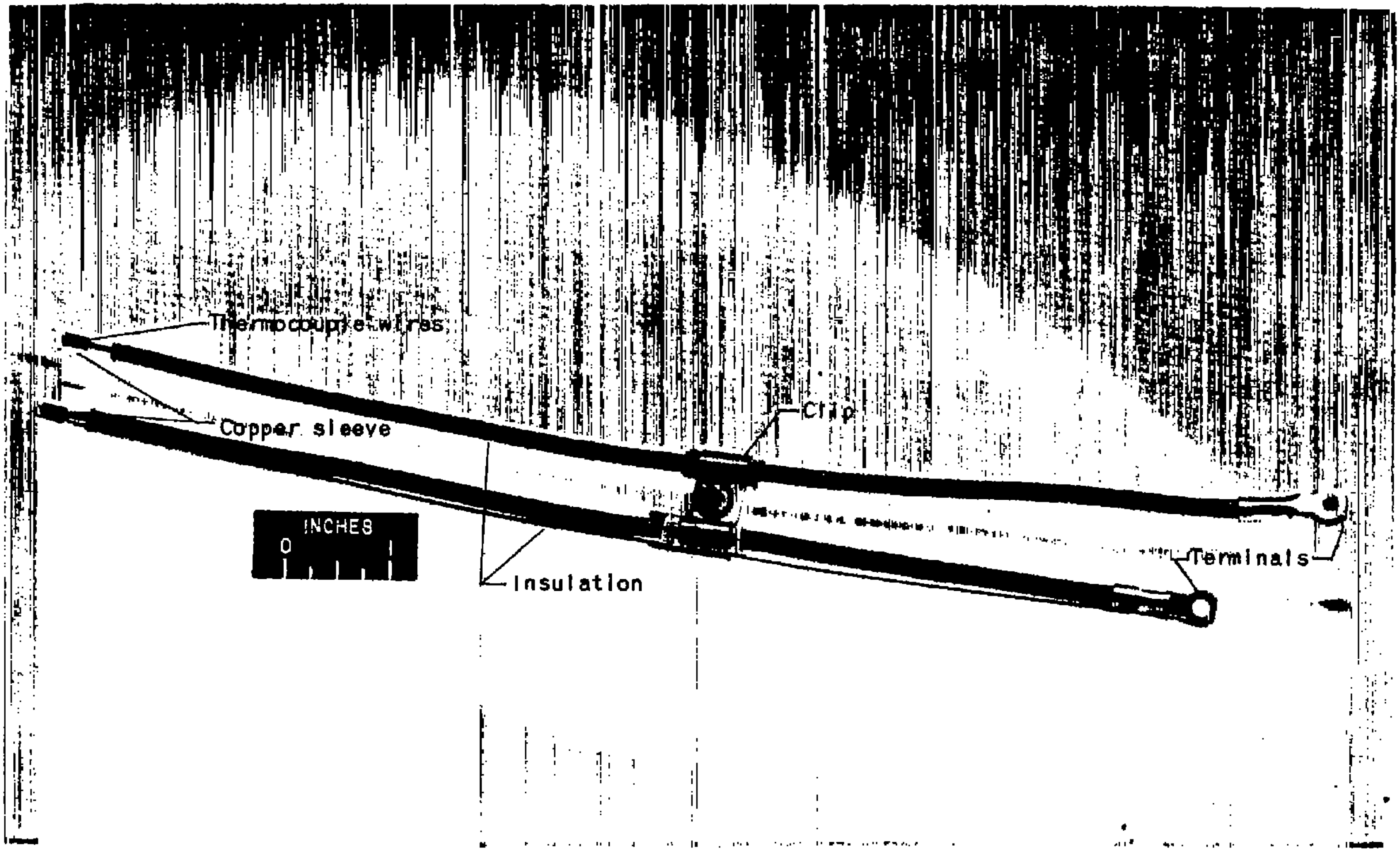


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Figure 8. - Standard Army-Navy-Commerce barrel-flange thermocouple.

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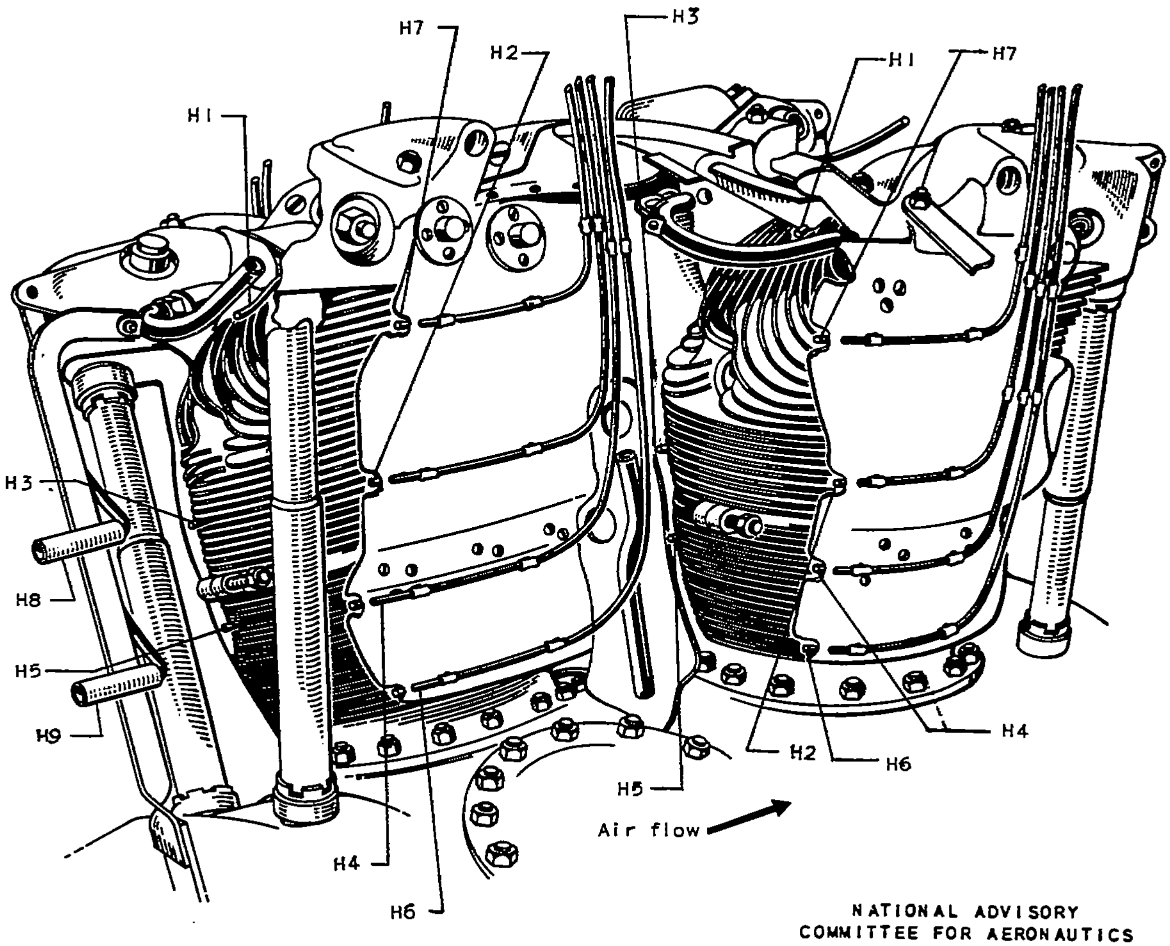

Figure 9. – Front- and rear-row cylinders showing total-head-tube installation.

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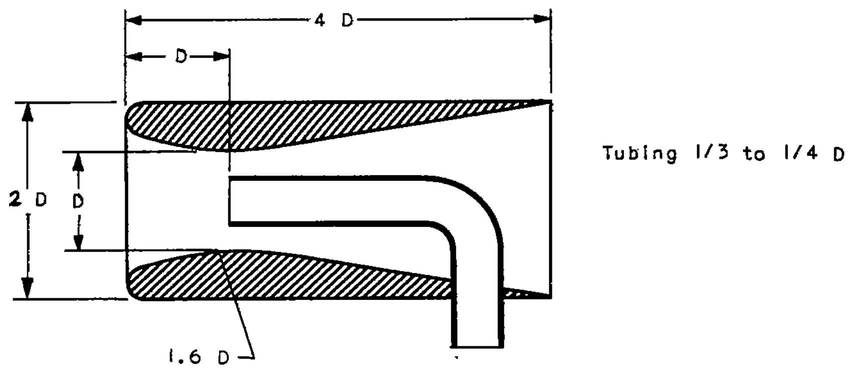
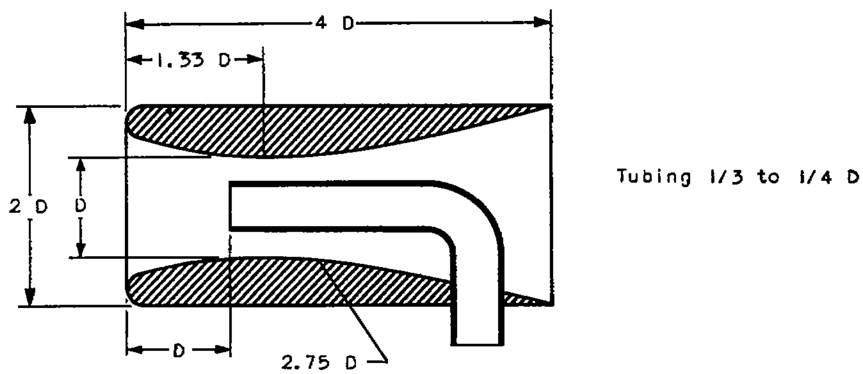


(a) Design 1.



(b) Design 2.

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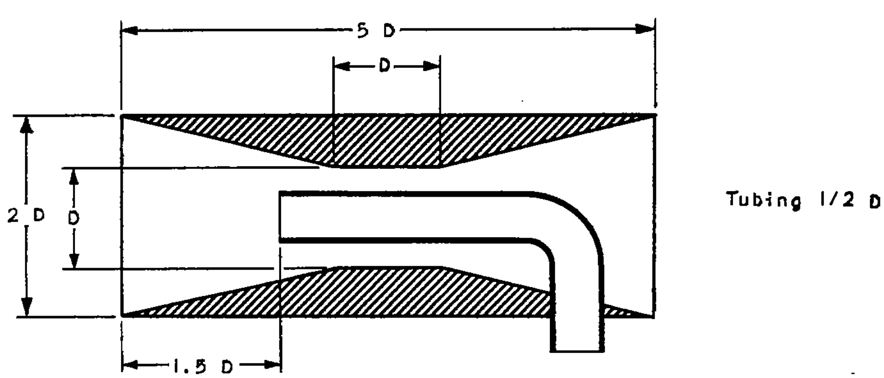
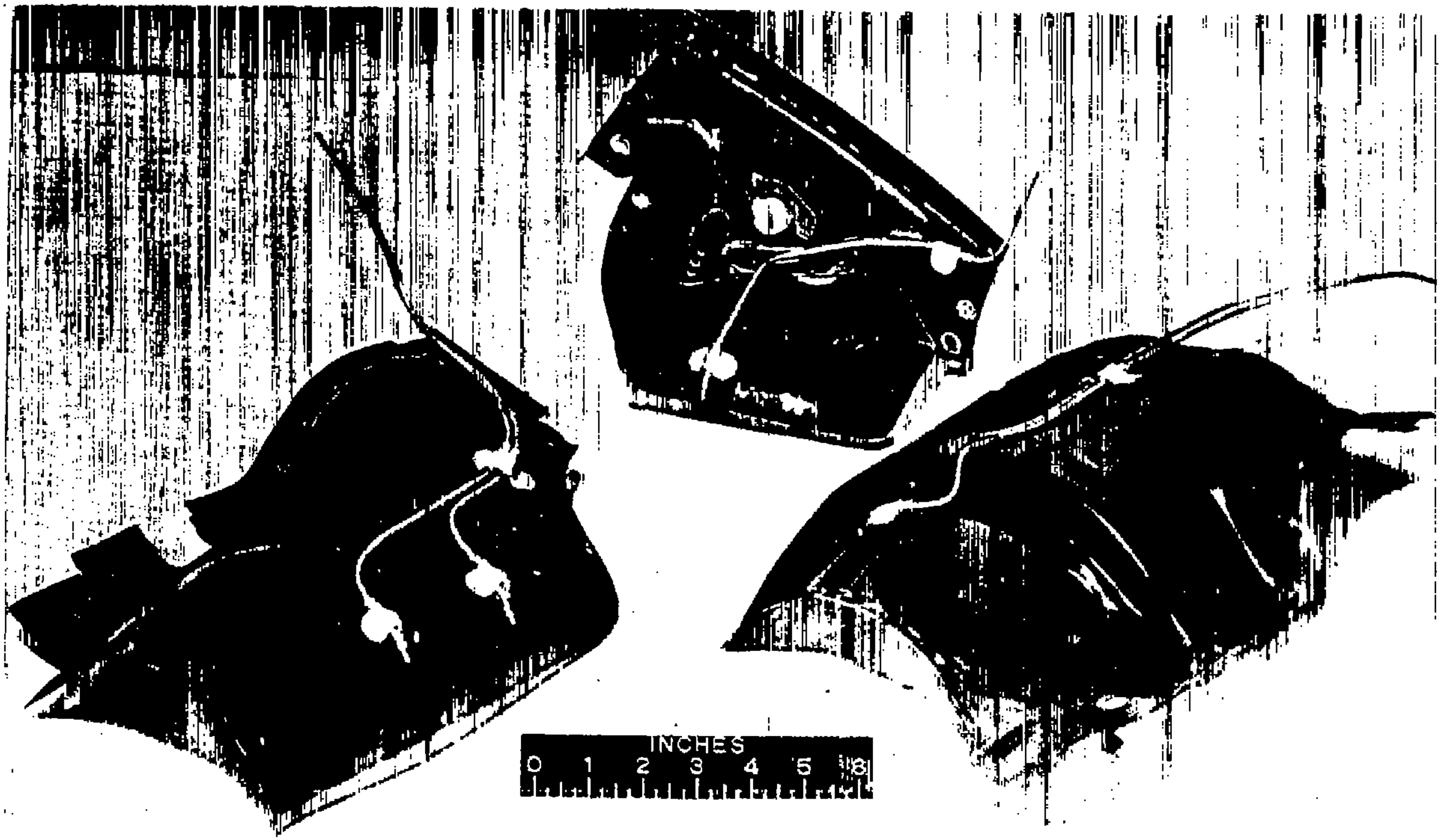


(c) Design 3.

Figure 10. - Designs of shrouded total-head tubes used in cooling investigations.



(a) View of cylinder baffles.

Figure 11. - Details of installation of total-head open-end tubes on baffles.

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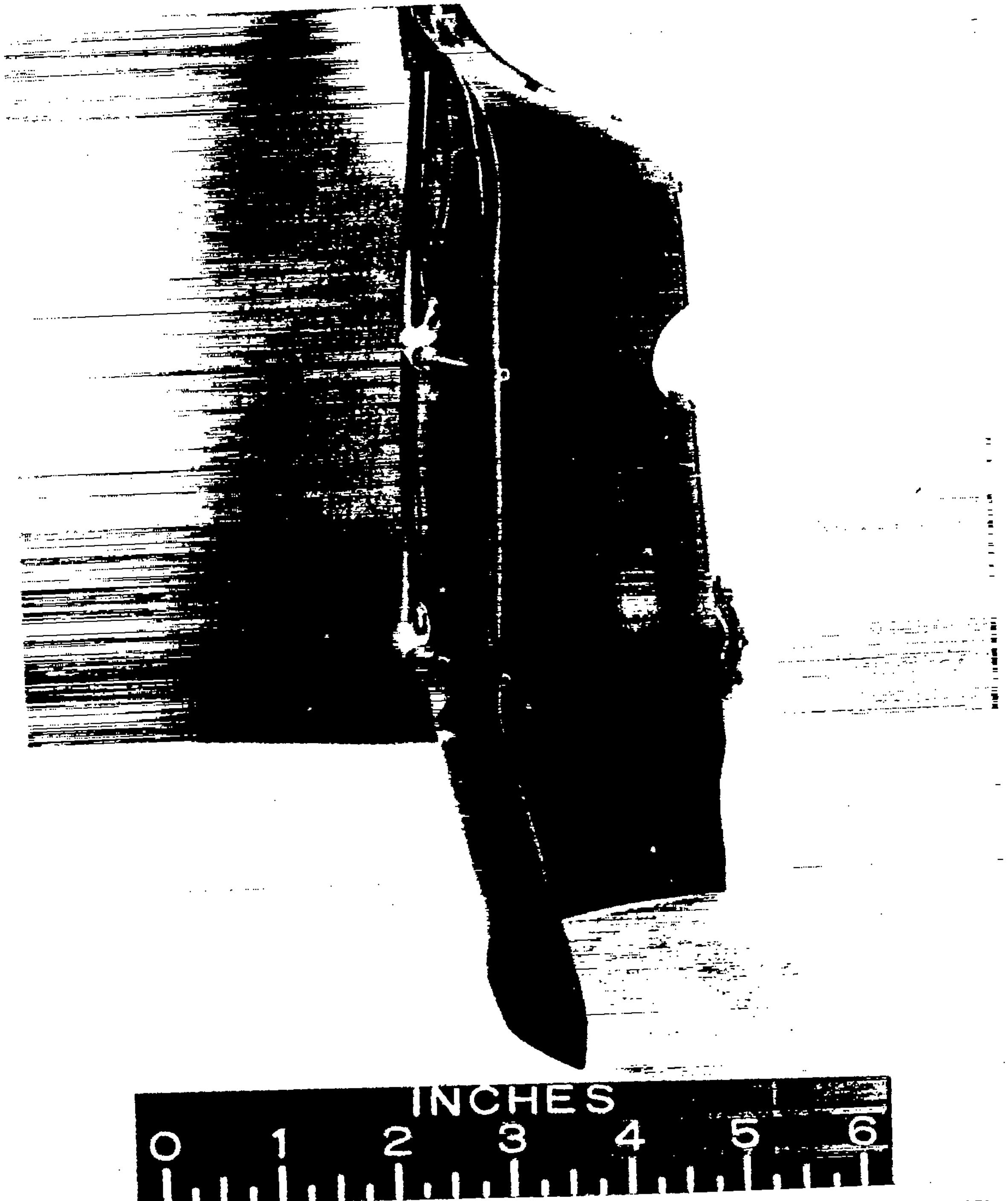

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(b) Front view of side baffle.

Figure 11. - Concluded. Details of installation of total-head open-end tubes on baffles.

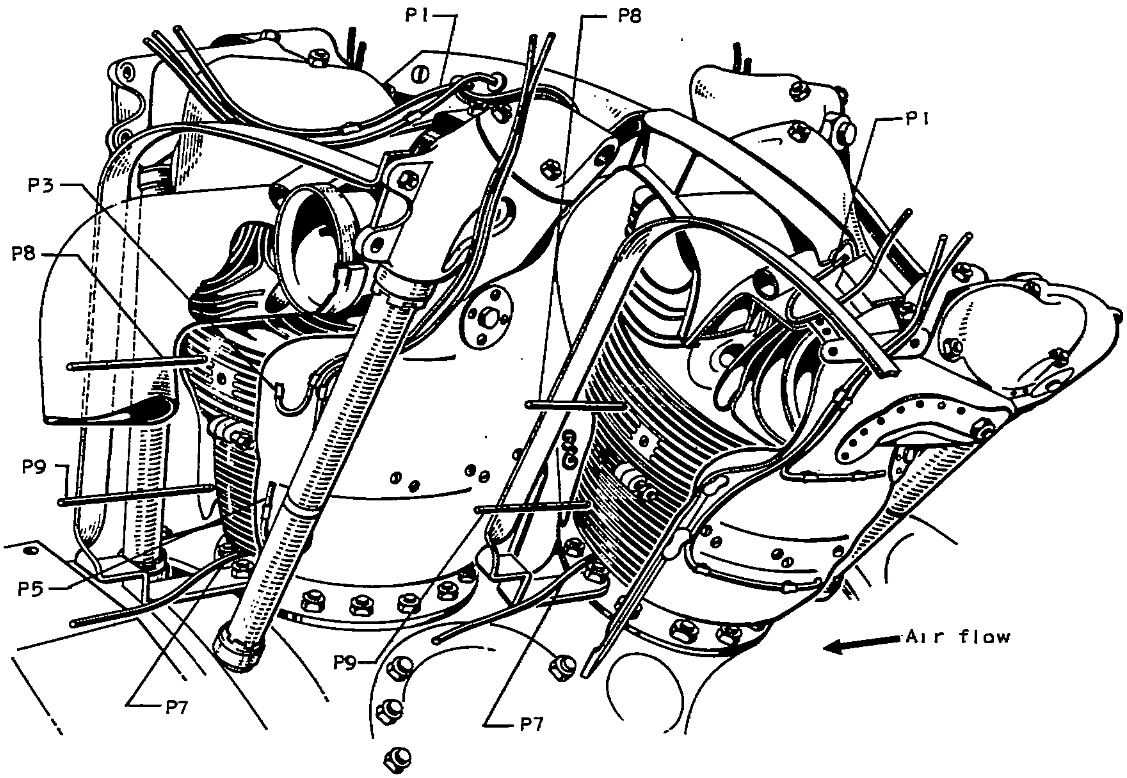

Figure 12. - Front- and rear-row cylinders showing static-pressure-tube locations.

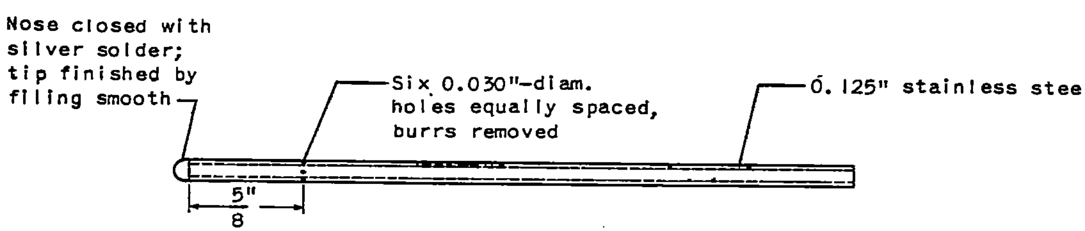

Figure 13. - Sketch of closed-end static-pressure tube used in cooling investigations.

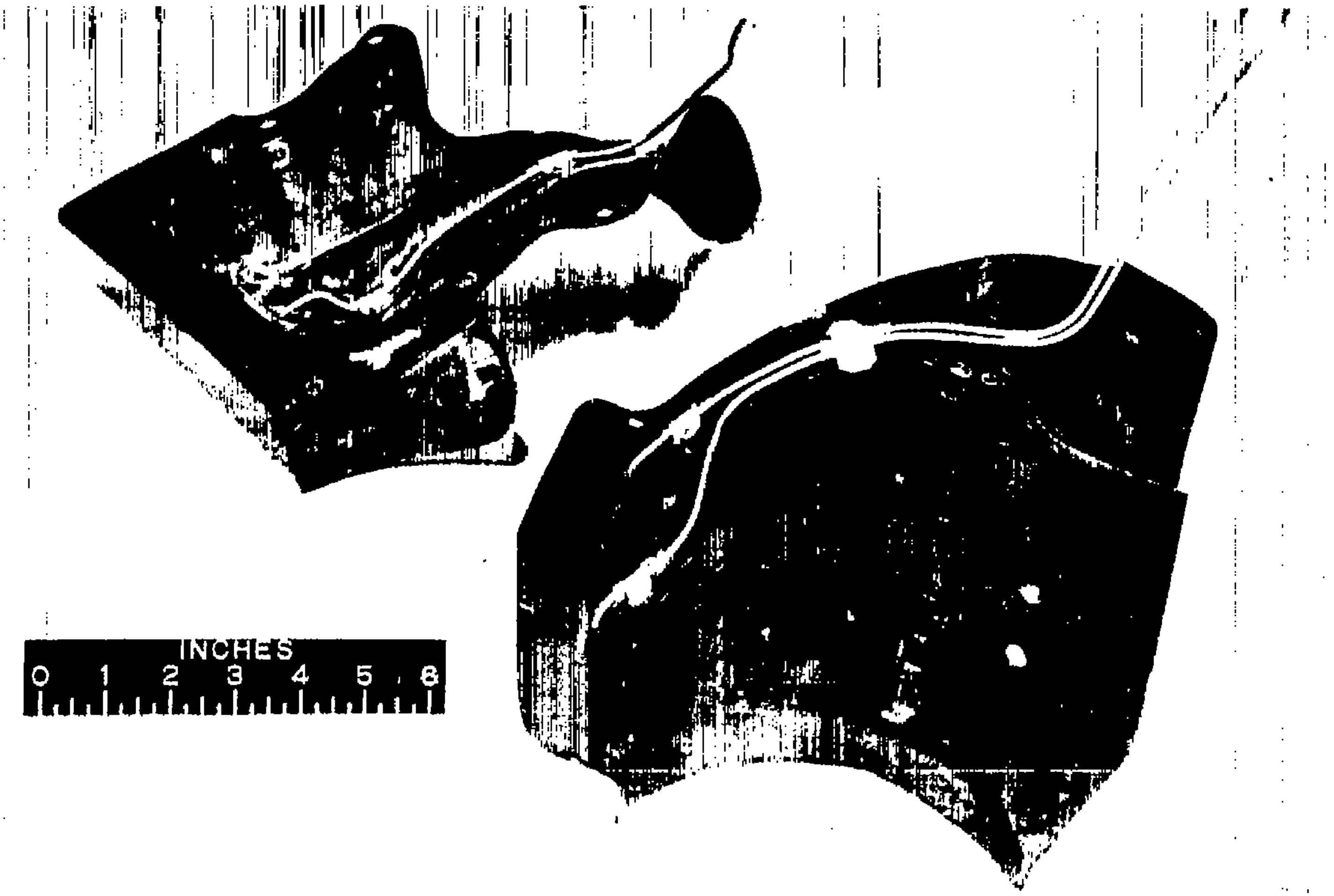

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Figure 14. - Details of installation of static-pressure open-end tubes on baffles.

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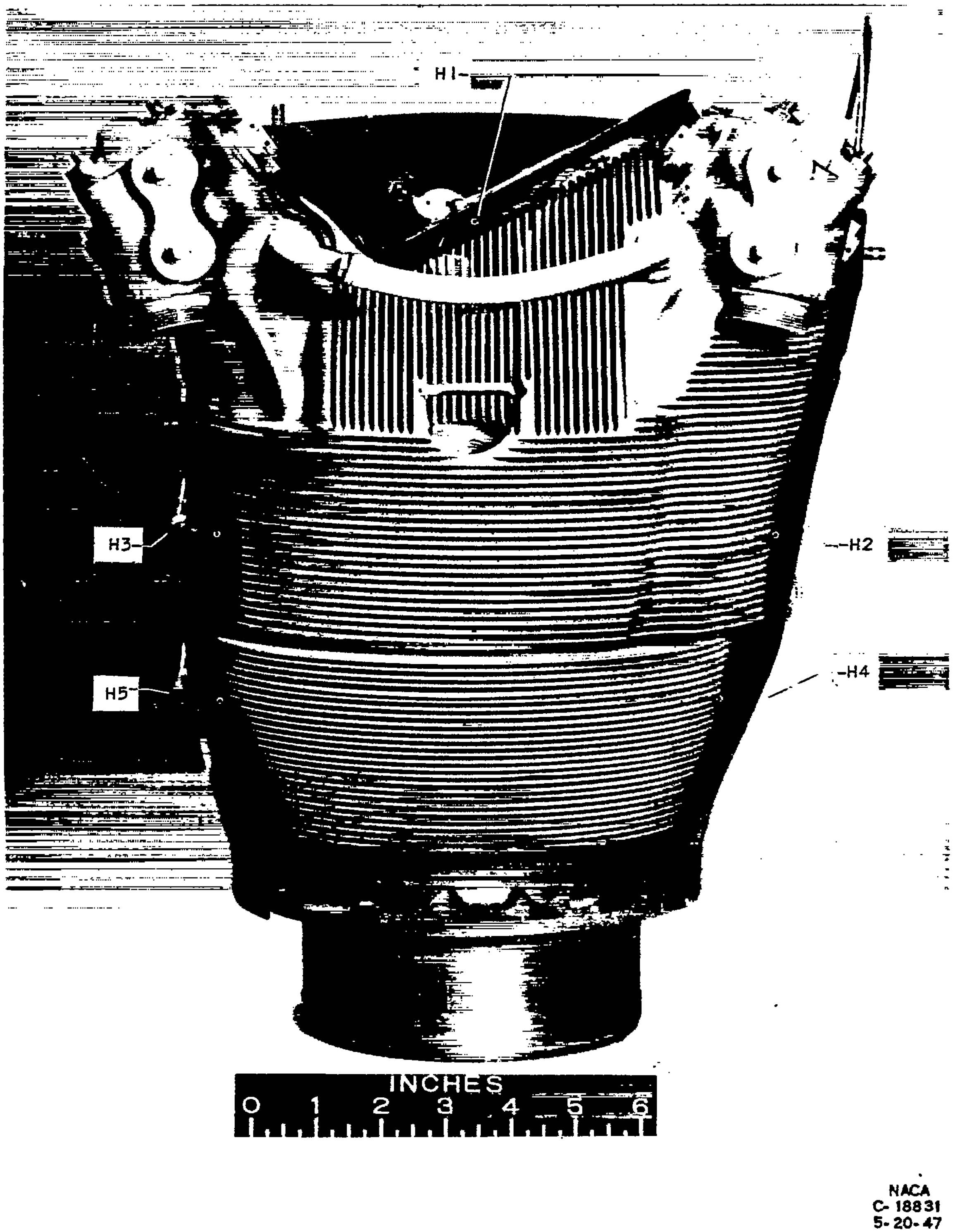

Figure 15. - Location of total-head tubes on cylinder (front view).

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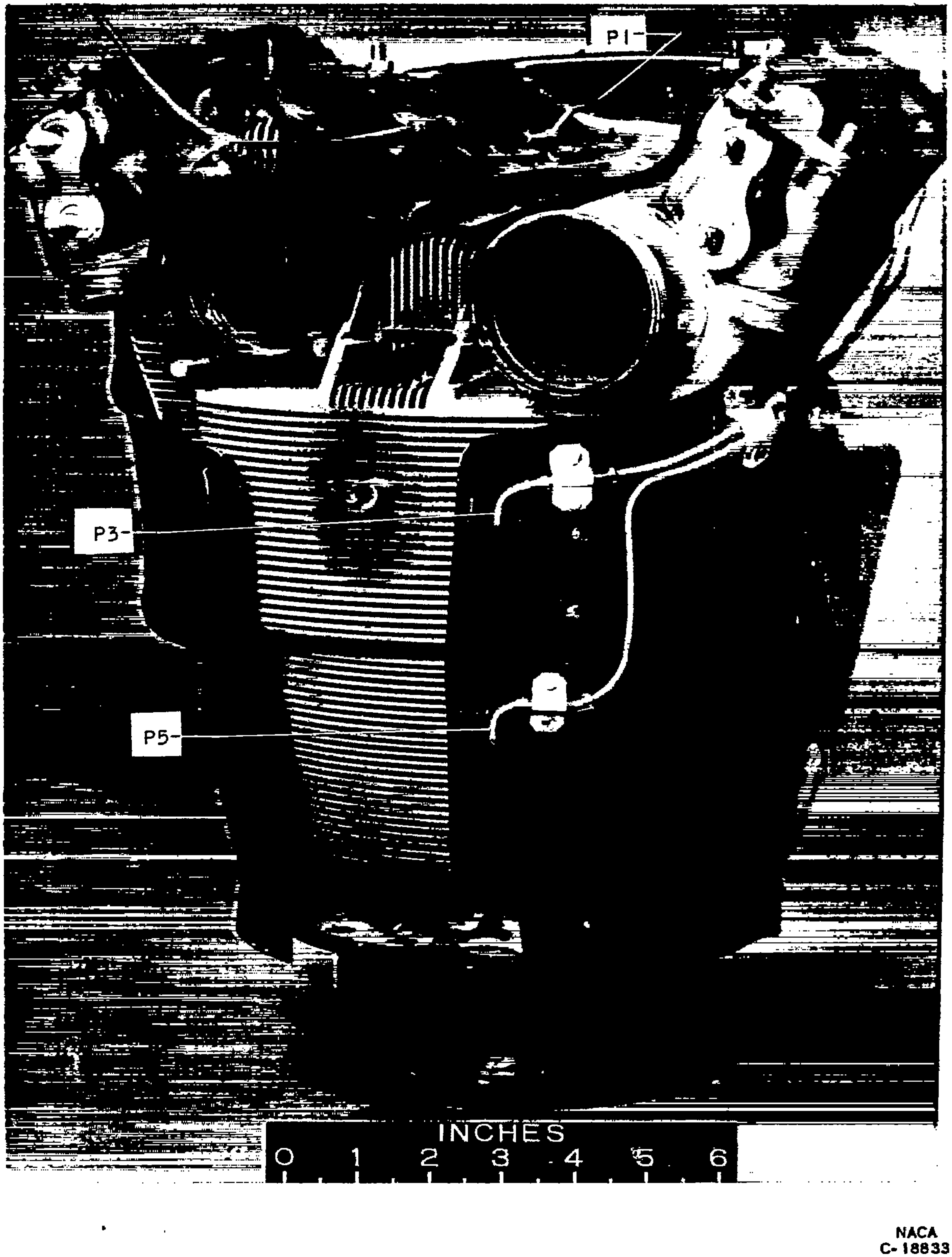

Figure 16. – Location of static-pressure tubes on cylinder (rear view).

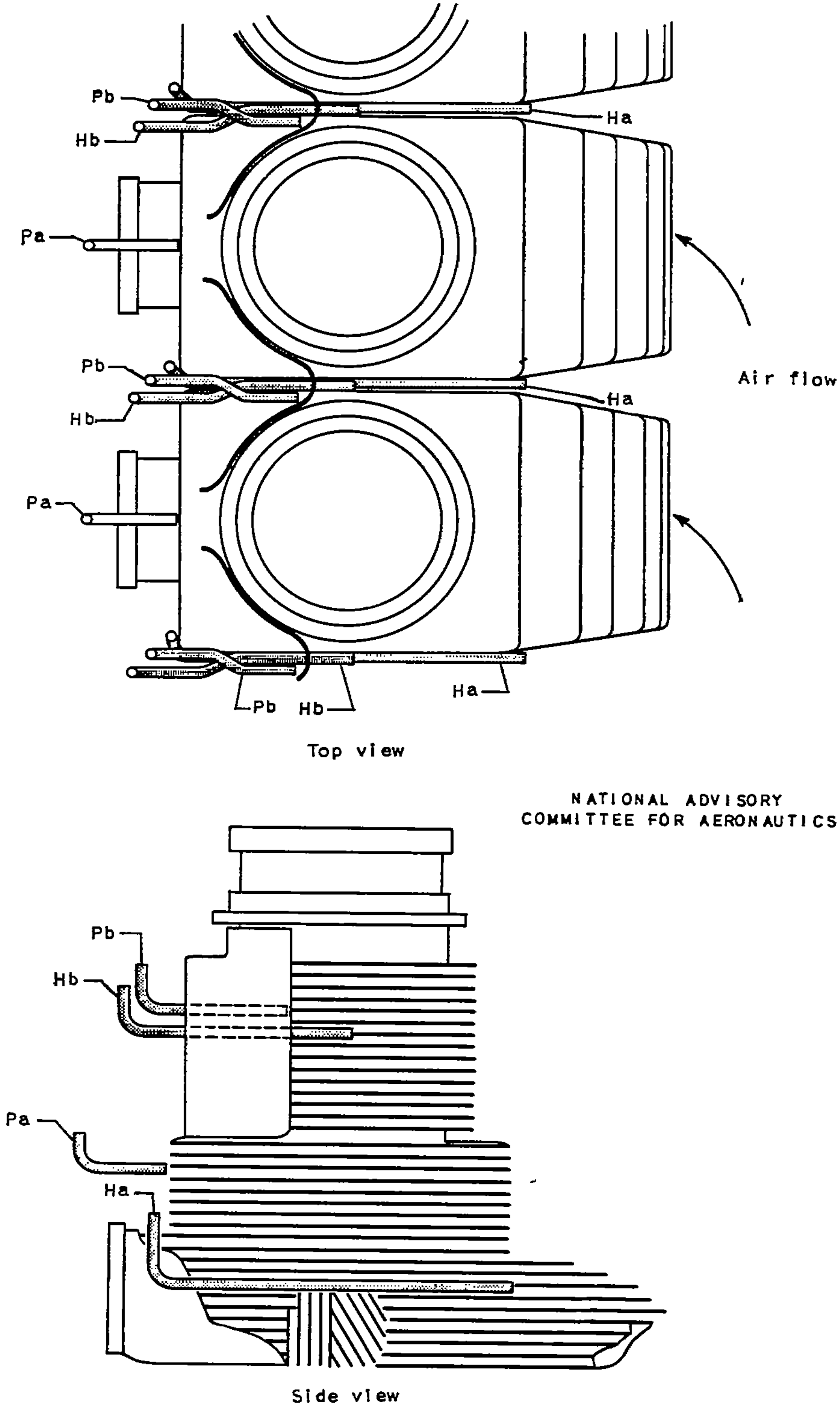

Figure 17. - Pressure-tube installation used on in-line air-cooled engine.